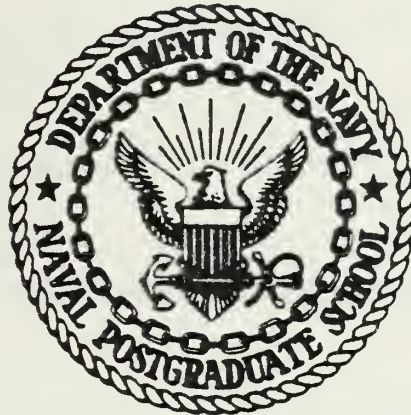


NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

APPLICATION OF COMPUTER MODELING TO THE
STUDY OF THE THERMODYNAMIC
FORCES ACTING ON A BUILDING

by

Peter J. Ibert

June 1982

Thesis Advisor:

H. A. Titus

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Application of Computer Modeling to the Study of
the Thermodynamic Forces Acting on a Building

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The object of this research was to model an actual structure, Bullard Hall, in order to devise a more energy efficient means to control the internal temperature of that structure. The research included a study of all major thermodynamic forces acting on the structure, including solar radiation. Once the model was developed it was compared with the actual structure to determine its usefulness.

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I. INTRODUCTION

To design and implement an optimal control scheme, the designer must first understand the dynamics of the system to be controlled. Usually the control engineer works with the transfer function of the system; either derived from the impulse response or by computing the transfer function from a model of the system. In the study of thermal structural analysis, it is extremely difficult to devise a simple transfer function due to the complexity of the system and the variety of the forces acting on a structure. To obtain the impulse response of an actual structure would require the expenditure of large amounts of energy and the development of some set of standards with which to judge the response, this method of obtaining the transfer function was considered, but proved too difficult to obtain useful data. With the advent of the computer, the engineer can now construct models of the system using equations to describe the system and its environment. These equations can later be used to determine which parameters or forces have the most effect on the system, and by considering only the major forces acting on the system a smaller model and eventually a usable transfer function can be derived.

The objective of this research was to develop a working model of the thermodynamic system consisting of the internal environment of Bullard Hall and the forces acting on that structure which would affect the internal environment. This structure was selected for its simplicity and availability, and once the building was modeled, the model could be used to devise more cost effective means to conserve energy while maintaining the comfort of the personnel in the structure. Due to the complexity of the modeling process, the time involved, and the lack of sufficient recorded data an actual working control scheme was not developed.

In Chapter II the appropriate energy equations for the structure are stated and simplified to make the problem realizable. All the major sources of energy loss and gain are discussed and modeled for inclusion in an overall system model. Particular emphasis is made to model the solar energy portion of the system in an attempt to better utilize that particular energy resource.

Chapter III is a compilation of the formulas derived in Chapter II and a computer run using the model compared with actual data. Chapter III also explores the use of cost functions and how they would be used to design an optimal control system to reduce the use of nonrenewable energy sources while keeping the building comfortable.

Chapter IV discusses the problems encountered in the collection of usable data for the model and the instrumentation used. This chapter also provides suggestions for future work in the area of instrumentation development and control studies in the area of energy conservation.

The final chapter summarizes the results of this investigation and presents conclusions and suggestions that might be considered for further study.

II. THEORY AND THE MODEL

The object of a model is to portray the appearance, nature, or performance of a device or system. It is assumed that with sufficient information a set of mathematical equations or formulas can be derived which will allow the modeler to emulate any particular component or collection of components of a system. Once a model has been created and verified to actually emulate the real system, the modeler can then change parameters in the model and study the effects of these changes. If a particular response is desired from the actual system, the model can be used to test the effects of changes on the system before costly changes are made. The use of a model to study the effects of changes in a system is part of the science of controls, and if a specific effect or overall condition is specified, with some necessary tradeoffs, the process then becomes one of finding the optimum control. This model is used to describe the thermodynamic effects of the building (Bullard Hall) by the air, internal equipment, and solar radiation surrounding or acting on the structure. Once verified, a suitable cost function or set of values will be selected to find the optimum control for the building's internal temperature. The major concern is to obtain maximum comfort for the

people who must occupy the building while using the minimum amount of energy. In order to simulate the thermodynamic properties of a building, certain information must be collected, simplified, and condensed into a model. The first problem is to define the system and its boundaries. For the purposes of this model the building was considered to be a constant volume system. This assumption leads immediately to the energy conservation equation for a constant volume [1], the equation is:

$$\dot{W}_S + \dot{Q} + \dot{M}(e + Pv)_{in} = \dot{M}(m + Pv)_{out} + \Delta E/dt$$

\dot{W}_S = Rate of Shaft Work or energy transferred to the system as work in BTU/hr.

\dot{Q} = Rate of energy transferred to the system as heat in BTU/hr.

\dot{M} = Mass flow across the system boundary in lb./hr.

$(e+Pv)$ = Energy contained in the mass crossing the system boundary in BTU/lb.

$\Delta E/dt$ = Change in energy storage term in BTU/hr.

At this point some simplifying assumptions are made:

1) There is no energy transferred to the building as work done on the system boundary.

2) The PV term for both the incoming flow and exiting flow is equal. This assumption is reasonable, since it

requires approximately the same amount of energy to get into the building as it does out.

3) The energy that is stored in the building is stored only as internal energy; there are no mechanical or chemical storage units in the building.

4) The energy storage medium of the building is its mass, not the people, machinery, or furniture in the building. This last assumption allows us to express the energy storage term as:

$$\Delta E/dt = M \times C_p \times dT/dt$$

where M is the total mass of the building, C_p is the Specific Heat capacity of the mass substance and dT/dt is the rate of temperature change of the building's mass.

The original equation now reduces to:

$$\dot{Q} + \dot{M}(e_{in} - e_{out}) = M \times C_p \times dT/dt$$

At this point some further simplifying assumptions are made.

5) The energy storage medium of Bullard Hall will be the concrete mass of the building.

6) The air inside the building will be assumed to be in thermal equilibrium with the internal concrete walls. This assumption allows one to take air temperature in the building as if it were the temperature of the mass. During data

acquisition this assumption proved to be quite accurate for the air temperature for particular regions of the building differed from the wall temperature by no more than 2.0 degrees.

7) Since the system is so massive, it possesses a very slow response time, and therefore data were taken hourly.

Heat loss and gain $\{\dot{Q} + \dot{M}(e_{in} - e_{out})\}$ of any system can occur in three ways: conduction, convection, and radiation. These three methods will be discussed later in the form of envelope loss, infiltration, and solar gain. It is important to note that all the heat loss and gain terms are considered together. During the 1960's and 70's, most literature and textbooks on building heating and cooling only considered solar heat gain as a load on the air-conditioning system and did not consider it as a contributor in heating a building. In the particular case of Bullard Hall, the solar gain is substantial and can not be ignored.

The actual mass of the building is the sum of the machinery, air, and the physical structure. In this model we will only consider the mass of the structure since the total mass of the air plus the machinery in the building together amounts to less than 2% of the building mass. For a low mass structure the air and machinery may be a significant quantity, but in this case it is not. The building mass was calculated using the blueprints [2] and the 1952

building specifications [3]. The following table is a listing of those calculations:

ITEM	NUMBER	DIMENSIONS	VOLUME ft. ³
Slabs			
Bottom floor	1	132'2" x 132'2" x 5	7,278.02
Middle floor	1	132'2" x 132'2" x 14"	20,379.36
Roof	1	132'2" x 132'2" x 6"	8,665.05
Supports			
Interior	32	14.5" x 14.5" x 24'4"	1,136.90
Exterior	20	18.5" x 14.5" x 24'4"	906.58
Joiners	48	2' x 1.5' x 126'1.5"	18,162.00
Total Volume			56,527.93

Thus the mass is:

$$\text{Mass} = M = 56,527.93 \text{ ft}^3 \times 150 \text{ lb./ft}^3 = 8,479,189.5 \text{ lb.}$$

Using the tables in the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Guide and Data Book [4], to obtain the specific heat capacity of concrete ($C_{pc} = 0.156 \text{ BTU/lb.}^{\circ}\text{F}$), a constant representing the building energy storage capacity was computed:

$$M \times C_{pc} = 8,479,189 \text{ lb.} \times 0.156 \text{ BTU/lb.}^{\circ}\text{F} = 1,322,753 \text{ BTU}/^{\circ}\text{F}$$

A. ENVELOPE HEAT LOSS AND GAIN (CONDUCTION)

Conduction of energy through the building envelope is the largest loss term in the energy balance equation. The building envelope is defined as "All external surfaces which are subject to climatic impact; for example, walls, windows, roof, floor, etc" [5]. Architects and engineers have developed a method for determining the amount of energy transferred through the envelope by simplifying the heat flow equation down to:

$$\dot{Q} = U \times A \times \Delta T$$

\dot{Q} = The total heat flow through the envelope
in BTU/hr.

U = The heat conduction coefficient for the
structure in BTU/hr. ft.²F.

A = The surface area of the structure in Ft.².

ΔT = The temperature difference between internal
and external air temperature in °F.

This formula and the method from which it is derived is explained in detail in the ASHRAE Guide and Data Book. A brief explanation of the formula will be discussed, but it is by no means comprehensive.

Around the year 1928, a theory of how heat conduction through a substance could be modeled was presented. This method was based on the analogy of a material's heat

transfer characteristics to an electrical circuit. The theory spurred research into determining the value and validity of the theory, and in 1942, the American Society of Heating and Ventilation Engineers (later to become ASHRAE) adopted a standard for testing materials. The theory was simple enough. The ability of a material or substance to resist the flow of heat through it would be analogous to the resistance in an electrical component to the flow of current. The temperature difference across the substance would be the driving potential, and the "current" through the substance would be the heat flow. The early theory was based on steady-state conditions, but later analysis proved the theory was more than adequate to model the heat flow under dynamic or changing conditions. The theory stated that if a collection of materials or substances were stacked together, then the total resistance to heat flow of the stack would be the sum of the individual resistances. In the electrical analogy this would be equivalent to the resistances being in series, and the total resistance of an n-element series circuit is:

$$R_t = \sum_{i=1}^{i=n} R_i$$

R_t = The total resistance of the series circuit.

R_i = The individual resistance of each element or material.

The total thermal resistance (R_t) is the reciprocal of the thermal conductance (U) and the value of (U) is the most important quantity to the engineer or architect in the heat conduction equation and in the study of an energy efficient building. The smaller the value of thermal conductance, the less heat or energy will be lost by the building for a given temperature difference between the inside and outside environment. It should be noted that this also applies when one is trying to cool the inside of a structure. The calculation of the envelope heat loss requires the calculation of two constants, the thermal conductance and the surface area. The calculation of ΔT requires knowledge of the internal and external temperature, both variables, and not precomputable.

A single number representing the total surface area of the building is not useful, since for different structural members the thermal conductance (U) differs and each partial surface area must be individually computed. Bullard Hall is divided into six surfaces; the roof, floor, and the four walls. None of these surfaces are homogeneous, so their individual areas must be calculated. The following table is a computation for those different areas:

Surface	Number	Material	Dimensions	Area ft ²
Floor	1	concrete	132'2" x 132'2"	17,468.02
Roof				
Vents	2	metal	3'4.5" x 3'4.5"	22.78
Skylights	9	plastic	3'5.5" x 3'5.5"	107.64
Scuttle	1	metal	3' x 2'6"	7.5
Roof area	1	tar + rock		17,330.10
Walls				
Glass		1/4" glass		8,280.57
Wood		1" -6" pine		3,415.64
Concrete				19,379.22

The thermal conductance for each type of surface must be calculated. In Appendix A a set of drawings of the building's surface materials and how they are assembled is presented. Along with the drawings are the computations for the thermal resistance of each structure. The following table is a collection of that information:

Surface	Thermal Conductance (BTU/hr. ft. ² °F)
Floor	0.48
Roof	
Vents	1.63
Skylights	1.15
Scuttle	1.63
Roof area	0.17
Walls	
Glass	1.1
Wood	1.0
Concrete	0.61

The only remaining computation is the complete building heat loss coefficient ($U \times A$). The total envelope heat loss constant is the summation of all the areas times the respective thermal conductance. Using the information from the previous tables, the following table is a computation of that constant.

Surface	Area	U	U x A
Floor	17,468.02	0.48	8,384.65
Roof			
Vents	22.78	1.63	37.13
Skylights	107.64	1.15	131.78
Scuttles	7.5	1.63	12.22
Roof area	17,330.10	0.17	2,946.11
Walls			
Glass	8,280.57	1.13	9,357.04
Wood	3,415.64	1.00	3,415.64
Concrete	2,049.18	0.61	1,249.99
Total	(BTU/hr.°F)		17,149.91*

* This figure does not include the constant for heat loss through the floor because the floor is not subject to the exterior air temperature, but the ground temperature.

B. INFILTRATION (CONVECTION)

Convection losses in a building are caused by the flow of outside air through the building being heated and then exhausted back to the environment. This loss is called infiltration and the cause for this loss is the pressure difference across the building's surfaces. These pressure differences are caused by two different conditions: the

temperature difference between the inside and outside and the flow of wind across the surfaces of the building. Both of these effects cause the air to flow in and out of any openings in the surface of the building. A large body of data from the 1940's exists on these heat flow mechanisms but no practical model has been yet developed. This is made evident by the request for proposals made in 1980 by the Department of Energy for a suitable model of the air flow through the openings in a structure. A short explanation of these effects follows.

When a temperature difference exists between any two areas there is a natural flow of air from the colder area to the warmer area due to the density difference of the air. This density difference causes the warmer air to rise and the colder air to settle in the lower areas. This difference causes what is called the chimney effect. When the air in a building is warmer than the outside air a high pressure area is set up in the higher levels of the building and the warm air flows out of the upper levels. At the same time, a low pressure area is established near the floor or lower levels; this low pressure draws air into the building from the outside.

To calculate the differential pressure across a building the engineer must first determine the building's neutral zone or the level above the lowest level or floor where the

temperature is average. Once this has been determined the engineer can then compute the total differential pressure across the building. Next, the engineer must locate all openings in the building envelope, calculate their distance from the neutral zone, and compute the air flow through that opening because of the pressure differential.

As air flows over a surface, high and low pressure areas are created whose pressure magnitudes depend on the angle between the wind and the surface of the structure as well as the velocity of the wind across the surface. This effect is similar to the lift created on an airplane wing and is called the Venturi principle. On the windward side of the structure a high pressure area develops and on the leeward side a low pressure area is developed. This differential pressure causes the flow of air through the building which is independent of the temperature difference that exists in the building. Again the theory is simple but the actual calculation and determination of the overall effect is difficult. Wind speed over the building surfaces is not always uniform and therefore an averaged estimate is used. If the exact weather conditions for a given period were known, then with a reasonable amount of calculation, the engineer may have some idea of what actually occurred. But without a complete set of data, the engineer would only be guessing at the actual differential pressures involved.

An engineer or architect would not actually calculate the effects of the wind and the thermal difference; in fact, he would employ another estimate to approximate the effects of both conditions. The ASHRAE Guide gives a method for estimating the overall effects on the building by expressing the heat loss in terms of the total number of times the entire air mass in the structure is replaced or turned over. For most structures, the turnover rate is one to two and a half times the total volume each hour, with allowances made for the orientation and location of openings in the building. Again most of the work on this method of heat transfer was done around the 1940's and 50's. The basic equation for determining the energy loss is:

$$\dot{Q} = V \times \text{coeff.} \times C_{p_a} \times p \times (T_{\text{ext}} - T_{\text{int}})$$

$$\dot{Q} = \text{Energy lost in BTU/hr.}$$

$$V = \text{The volume of the structure in ft.}^3$$

$$C_{p_a} = \text{The specific heat capacity of air } 0.24 \text{ BTU/lb.}-^{\circ}\text{F}$$

$$p = \text{The density of air } 0.075 \text{ lb./ft.}^3$$

$$T_{\text{ext}} = \text{The external temperature in } ^{\circ}\text{F}$$

$$T_{\text{int}} = \text{The internal temperature in } ^{\circ}\text{F}$$

$$\text{Coeff.} = \text{The number of turnovers in one hour.}$$

Since Bullard Hall is not surrounded by windbreaks or major wind deflecting structures, and has windows on all sides, the turnover coefficient for Bullard Hall is selected

to be 2.5. The infiltration heat loss equation then simplifies to:

$$\dot{Q} = 454,168.22 * 2.5 * 1.08 * (T_{\text{ext}} - T_{\text{int}}) \text{ BTU/hr.}$$

→ This heat loss or gain term is included in the model as $\dot{M}(e_{\text{in}} - e_{\text{out}})$.

C. SOLAR GAIN (RADIATION)

Solar power or usable energy from solar radiation is a new energy field. Daniel Berhrman, in his 1976 book "Solar Energy The Awakening Science", concludes that man is just now realizing the potential for solar energy. But solar power has been used for hundreds of years, as far back as the middle ages. The American Pueblo Indians were building structures out of adobe clay using solar energy as their major source of heating, and cooling. Around the turn of the century, E. G. Morse studied the large mass heat storage system for solar energy, but not until 1976, when a Frenchman named Thrombe evaluated the large mass structure for storage and transmission of its heating properties, was this type of storage medium taken seriously. From Thrombe's studies, the theory and equations necessary for constructing a Thrombe Wall, which could be used to keep a structure cool during the daylight hours and provide heating through the night from stored energy were presented. The curious thing is that if a Thrombe Wall were constructed in the Arizona

desert made of adobe clay which would provide the optimum amount of heating and cooling, the thickness will be nearly the same thickness of the abode walls constructed by the Pueblo Indians more than 1000 years ago. The use of solar energy to dehydrate fruits and vegetables for storage and later consumption by the Indians was noted by the first colonists to settle in the new world, so the use of solar power is not new. In 1955, the International Solar Engineering Society was formed and held its first Solar Energy Symposium in Phoenix, Arizona. This group of engineers and educators preached the conservation of non-renewable energy sources and the use of renewable energy in the forms of solar and wind power. Until recently no one took this group seriously. In 1955, Daniels and Duffie published "Solar Energy", a book which predicted the energy problems of the 1970's and recommended the study and use of solar power as an alternative to petroleum products. The book contains examples of solar powered water heaters and concentrating solar collectors for providing high temperature water and steam for energy production.

Our sun is a star and a small star at that, but even so it produces about 3.8×10^{23} KW of energy each hour of this energy. Only 1.7×10^{14} kwh of energy reaches the earth's upper atmosphere and either through reradiation, absorption, or reflection only about a third of that energy

reaches the earth's surface [6]. Assuming 75% of the earth's surface is water and only 1% of the energy falling on the earth's remaining surface is utilized or converted into a usable energy source, this still amounts to 1.2×10^{17} kwh or better than 1600 times more energy used in the United States, in 1977 [7]. This amount of energy is substantial and represents a tremendous untapped resource.

In buildings and other structures, solar tracking is not nearly as important as determining how much of the sun's energy actually reaches the building's surface. To do this, one must know where the sun is in relation to the building's surfaces. The U.S. Naval Observatory in Washington D.C. publishes the "Nautical Almanac" (H.O. 214) yearly. This publication contains tabulated data which with a few simple calculations, the position, azimuth and elevation, of a star or planet can be obtained for celestial navigation, and one of those stars, is the sun. In order to understand how this data is available and how it is used a brief explanation of celestial navigation or astronomy is necessary.

Celestial navigation is performed in a spherical coordinate system. The center of the earth, is the center of the coordinate system. The equator provides one reference coordinate and a circle drawn through the north pole and Greenwich, England provides the other reference coordinate. With two coordinates any position on the earth's surface can

be specified, for example Bullard Hall is 36 degrees 35 minutes and 43 seconds North Lat. and 121 degrees 52 minutes 30 seconds West Long. [8]. This set of coordinates uniquely fixes the position of Bullard Hall on the face of the earth.

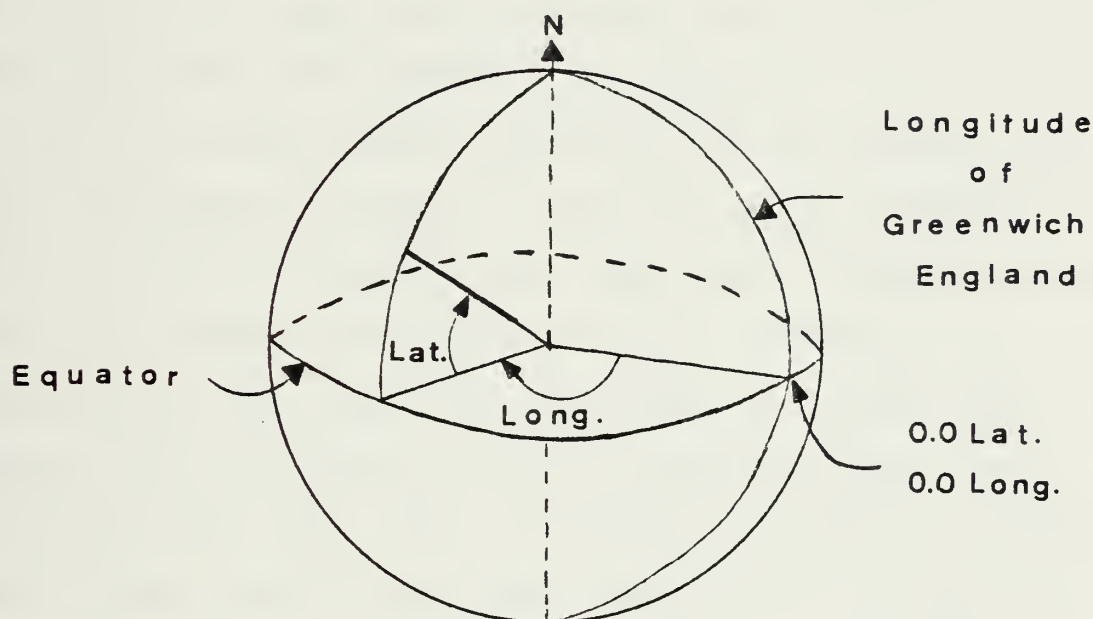


Figure 1
Celestial Coordinate System

Time is also an important quantity of interest and to standardize time all celestial time is measured from the time in Greenwich, Greenwich Mean Time or GMT.

A major assumption in celestial navigation is that all the light rays arriving from a star are parallel. This is a good assumption even for the sun since the maximum error for

the sun is 0.002 degrees or 8.7 sec. of arc. The difference is hard to measure, and is of little importance in the calculation of solar gain. Under these assumptions, the position of a star can also be uniquely given by a set of latitude and longitude coordinates, but in the case of a celestial body these coordinates are referred to as the declination and GHA, Greenwich Hour Angle.

With this short introduction one can now compute the sun's position at any time. First, the GMT is computed. This is done by noting the time zone (California is in time zone +8 or California is 8 hours behind Greenwich) and adding that to the local time expressed in 24-hour time. To compute GMT in California add 8 to the Local Time. This establishes the GMT. Next, one enters the Nautical Almanac with the date and GMT and reads the sun's GHA (Longitude) and declination (Latitude). From the GHA subtract the Longitude of the observer this is now referred to as the Local Hour Angle (LHA). Now applying Napier's rules for the solution of the celestial triangle for the sun's altitude and azimuth [9].

ALTITUDE =

$$\arcsine(\sin \text{LAT} \times \sin \text{DEC} + \cos \text{LAT} \times \cos \text{DEC} \times \cos \text{LHA})$$

AZIMUTH =

$$\arctan(\sin \text{LHA} / \cos \text{LHA} \times \sin \text{LAT} - \tan \text{DEC} \times \cos \text{LAT}))$$

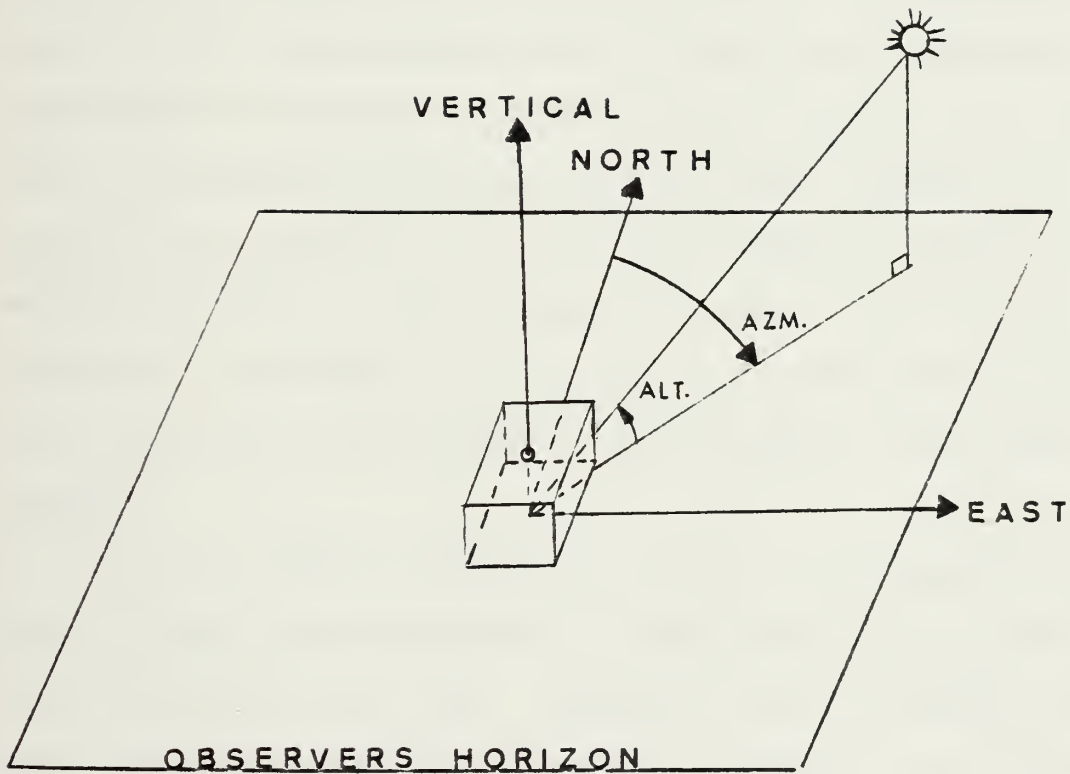


FIGURE 2
Sun's Relative Position

These two equations compute the altitude (the angular height above the horizon) and the azimuth (the angular measure from due North) of the celestial body.

In order to have a dynamic model of the sun's position, for continuous computation of the energy received, it was necessary to find a suitable method to approximate the sun's track continuously. This particular problem has already been solved by the U.S. Naval Observatory and in the publication "Almanac for Computers" which is published yearly. This publication uses a fifth-order polynomial to approximate the motion of the stars and planets and contains the coefficients to be loaded into a small computer to compute the position of a star at any time to within 6 seconds of error. The procedure will not be discussed because of its length, but copies of the publication and instructions can be obtained from the Naval Observatory on request.

If there were no atmosphere present, the earth's surface would receive the equivalent of 429.2 BTU of energy per square foot each hour [7]. Because of the atmosphere and the chemicals and particles in the atmosphere, the earth's surface receives only about 300 BTU per square foot per hour when the sun is directly overhead. The rest of the energy is absorbed or dispersed into the atmosphere. This fact of nature is referred to as diffusion and accounts for the blue

sky and the light we perceive as diffuse light in the atmosphere. This phenomenon of nature is discussed in most college level books on the subject of the atmosphere or light transmission. The actual process of how this energy is absorbed and then reradiated would require many equations and pages of text which is not worth the time to study in this thesis. The losses in the atmosphere still must be taken into account, but only in the simplest manner for our purposes. By using a device called a pyrliograph located at a site not too remote from the actual site, measurements were taken to determine how much energy was incident on the surface of the building; Appendix B is a collection of that data and the explanation of the approximations used. The approximations are based on the fact that the more atmosphere the sun has to penetrate, the more energy is diffused. The amount of energy received versus height is a sinusoidal function and can be approximated in a computer as a look-up table or a continuous function of values. For the modeling process used here the continuous approximation:

$$ALPHA = I_{max} \times \sin ALT$$

is used where ALT is the altitude of the sun above the horizon, and I_{max} is the maximum incident energy from the sun recorded on the pyrliograph for that day.

Once the amount of energy from the sun per square foot is tabulated another problem must be considered. While the sun traverses the sky the surface of the building which is normal to the sun's energy is changing, or, the total surface "seen" by the sun changes in relation to the sun. Since the energy of the sun on the ground has been calculated in square feet of surface which is seen by the sun, some type of formulation or scheme is needed to take into account this "seen" surface. The surface normal is a mathematical construct which defines a vector which is perpendicular to the surface and has a magnitude or length equal to the area of the surface. This vector now represents the total surface and can be manipulated vectorially. To find the image of some vector on another vector the operation of the dot product is used. If we consider the sun's position as the direction of the sun vector and the amount of energy as the length of this vector we now have a means of determining how much energy is received or incident on any surface. The dot product of the sun vector with the surface normal vector represents the energy incident on the surface. The following figures represent the mathematical construct of the normal vector and the dot product in graphical form.

The solar energy portion of the model has become extremely complicated at this point, and would appear to be

complete except for one thing; not all the energy incident on the building surface is absorbed by the surface. If the surface were mirror-like almost all of the energy would be reflected back into the atmosphere. If the surface were true black, almost all the energy would be absorbed by the surface. And if the surface was a perfectly clear glass most of the energy would be neither absorbed nor reflected, but would be transmitted through the glass. These three examples are the extreme cases and are easy to handle. The problem is that most buildings have an assortment of all three types of surfaces, in varying degrees. This variation is a real problem when one considers that the ability of a surface to absorb or reflect light energy may depend on the orientation of the surface to the light energy. Using the example of the glass mirror we find the following: If the sun is shining on the mirrored surface most of the energy is reflected. If the sun is shining on the rear of the mirror or leaded surface, most of the energy is absorbed. Finally, if the mirror surface is parallel to the light, most of the energy is transmitted through one edge of the glass and out the other. Again, most of the data collected and studied is from the early 1940's to the late 1950's, but the use of selected absorbers and reflectors in the collection of energy has sparked new studies in this area. The basic energy balance equation describing the problem from [10] is:

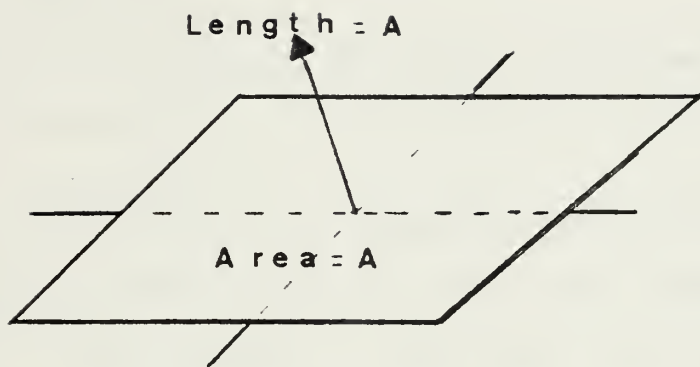


Figure 3
Surface Normal

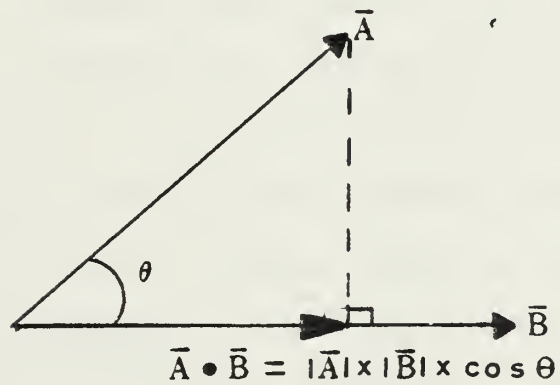


Figure 4
Dot Product

$$a + t + r = 1$$

a = percentage of energy absorbed by the material

t = percentage of the energy transmitted thru the material

r = percentage of the energy reflected by the material

The actual calculations of reflection coefficients were not done because of the lack of suitable test equipment and the complexity of the problem of assigning values for each incident angle of the sun on the various surfaces. An approximation for the total overall absorption coefficient was selected to be 0.85 mostly based on reports quoted in the 1950 book "Thermal Properties of Buildings" [11].

The final problem to be considered by this model was to include the effects of objects blocking the incident solar energy. Most structures do not stand isolated by themselves, but are usually grouped together causing the problem of shadowing. Shadowing reduces the amount of solar energy which eventually reaches the structure. If one wishes to receive the maximum amount of solar energy the structure must not be surrounded by objects which will shade the collecting surface. This shadowing may be from buildings, trees, or the general terrain surrounding the structure. Available these days are small hand held shadow angle

protractors. These devices are actually templates which chart the position of the sun (altitude and azimuth) for a specific latitude and time of day. The architect or builder orients the template to due south at the site where the structure is to be built. Then by noting the objects in the field of view of the template, he can determine when the structure will be shaded. Using this knowledge he can then recommend, using the site, or finding a better location. A shadow angle protractor was not used in the determination of the solar cutout angles for Bullard Hall. Instead, the time the sun first struck Bullard Hall was noted. Then, by use of the altitude and azimuth formulas taken from the U.S. Almanac for Computers the "cutout angle" was calculated to be 15 degrees above the observer's horizon and entered into the program. In the morning, after sunrise, the east and south faces of the building are partially shaded by trees and Spanagel Hall, the 15 degree solar cutout takes this shading into account. The west side of the building is shaded in the afternoon by trees and hills. The cutout for the west side was also calculated after observation and determined to be 34 degrees above the observers horizon.

D. AIR HANDLING AND CONDITIONING

An important item which so far has been omitted from the model is the air handling system. This item could be a substantial part of the building's environment and one of

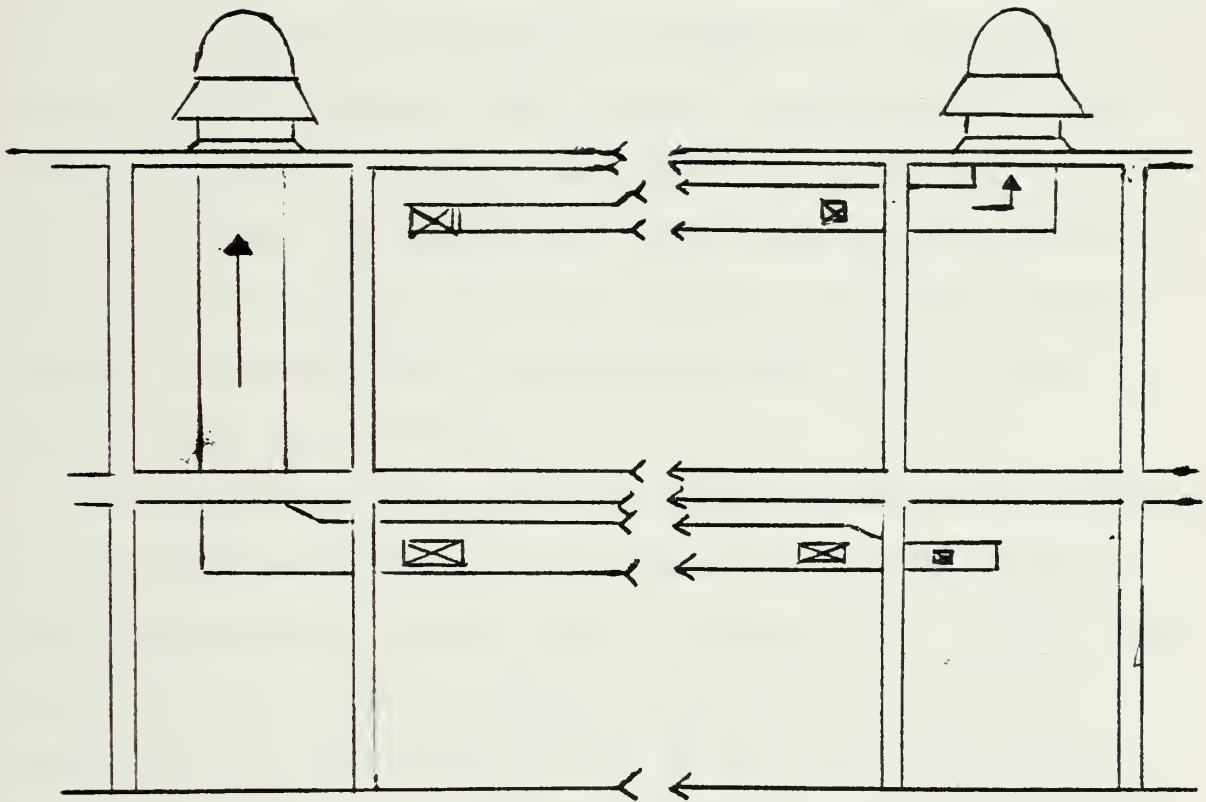


Figure 5
Air Handling Equipment

the chief resources available to the engineer in controlling the atmosphere in the structure. Supply and exhaust systems contribute to the infiltration losses by causing shifts in the neutral zone. They also provide a means of causing more air to be exchanged with the environment than the total effect of infiltration. The heating and air-conditioning systems can add or remove heat, humidify or dehumidify the air, and filter the atmosphere. The architect and builder have the most control of these systems, and these systems are the ones which must be considered when the optimum control strategy is devised.

Bullard Hall is an extremely simple system with respect to air handling systems. It contains only three exhaust fans and only one of these fans is normally on, the fan that takes a suction on the lavatory facilities. This fan exhausts nine hundred cubic feet of air per minute (CFM), and has already been considered in the infiltration losses. The other two fans (see Figure 5) are main exhaust fans, capable of removing 19,400 CFM from the building. Although installed, operational, and controllable through the Honeywell AD-1000 heating control system, the fans have not been on except for routine testing since the control system was installed. Therefore they were not considered in the dynamic model.

Bullard Hall has no air conditioning system but does contain 37 unit heaters dispersed about the first and second floors. These unit heaters are controlled individually or in groups of three by 25 thermostats placed throughout the building. A central thermostat controls the valve of the main steam supply to the building. The Honeywell system operates the steam supply valve opening it at preselected times and temperatures. If the temperature measured by the central thermostat on the lower floor of Bullard Hall indicates less than 65 degrees Fahrenheit and it is between 0600 and 1600 on a weekday the steam valve will open and allow steam into the building up to the heaters. If the local heater thermostats sense a temperature below their setpoints, the unit heaters will come on and heat the building. This on/off function is easily modeled as a step function which is activated when the internal temperature drops below 65 degrees and is zero when the temperature is above the 3-degree dead zone set into the thermostats. The heaters in Bullard Hall are capable of delivering 1,937,600 BTU/hr. which is equal to the maximum expected heating load on the building at the design temperature difference (internal temperature of 72 degrees and the outside temperature of 36 degrees).

E. PEOPLE AND MACHINERY

People and machinery in the building also add to the heat and cooling load, they usually provide such a small amount of energy as compared to the other sources that they are neglected except in unusual cases, such as high-density office buildings and computer operating spaces of buildings. The human body gives off an average of 400 BTU/hr. [4]. The major source of machinery heat in buildings, is in the form of lighting. (A 100-watt light bulb gives off about 340 BTU/hr.). Bullard Hall is seldom occupied by more than fifty people and the maximum number of lights noted during the period 1 June to 1 December 1980 was 85. Neither of these sources was ever significant though they are included in the model.

The biggest difficulty encountered in the modeling problem was with the people, but not that their presence could not be accounted for in the model. The problem was that people would leave the exterior doors on opposite sides of the building propped open which created a tremendous draft and more than doubled the infiltration losses. This problem was so acute that the only reliable and consistent data taken was when the building was nearly empty and the entrances could be watched.

III. COMPUTER MODEL SIMULATION

The digital model is one of the means available to the engineer to test possible modifications of a system without actually investing the resources in a modification. This is not to say that the model will truly simulate the system under all conditions, but with a good model, problems in a system can be spotted early and costly changes might not be necessary. The IBM 360-computer using the Digital Simulation Language package provided with the machine was used as the method for simulating the building. This system was chosen because the language is simple and easy to annotate, and the IBM 360-computer is normally the only one available to the student.

The following flow graph (Figure 6) is a pictorial representation of the computer programming used in the modeling of the building. The heart of the process is the integrator network where the output (TINT) represents the building's internal temperature. The driving force for a change in that internal temperature is lumped together in QTOT. This quantity is the \dot{Q} or rate of energy transferred to the system as heat in the energy balance equation derived in the model chapter. QTOT also contains the infiltration term $M(e_{in} - e_{out})$ derived in section II.B. of the model

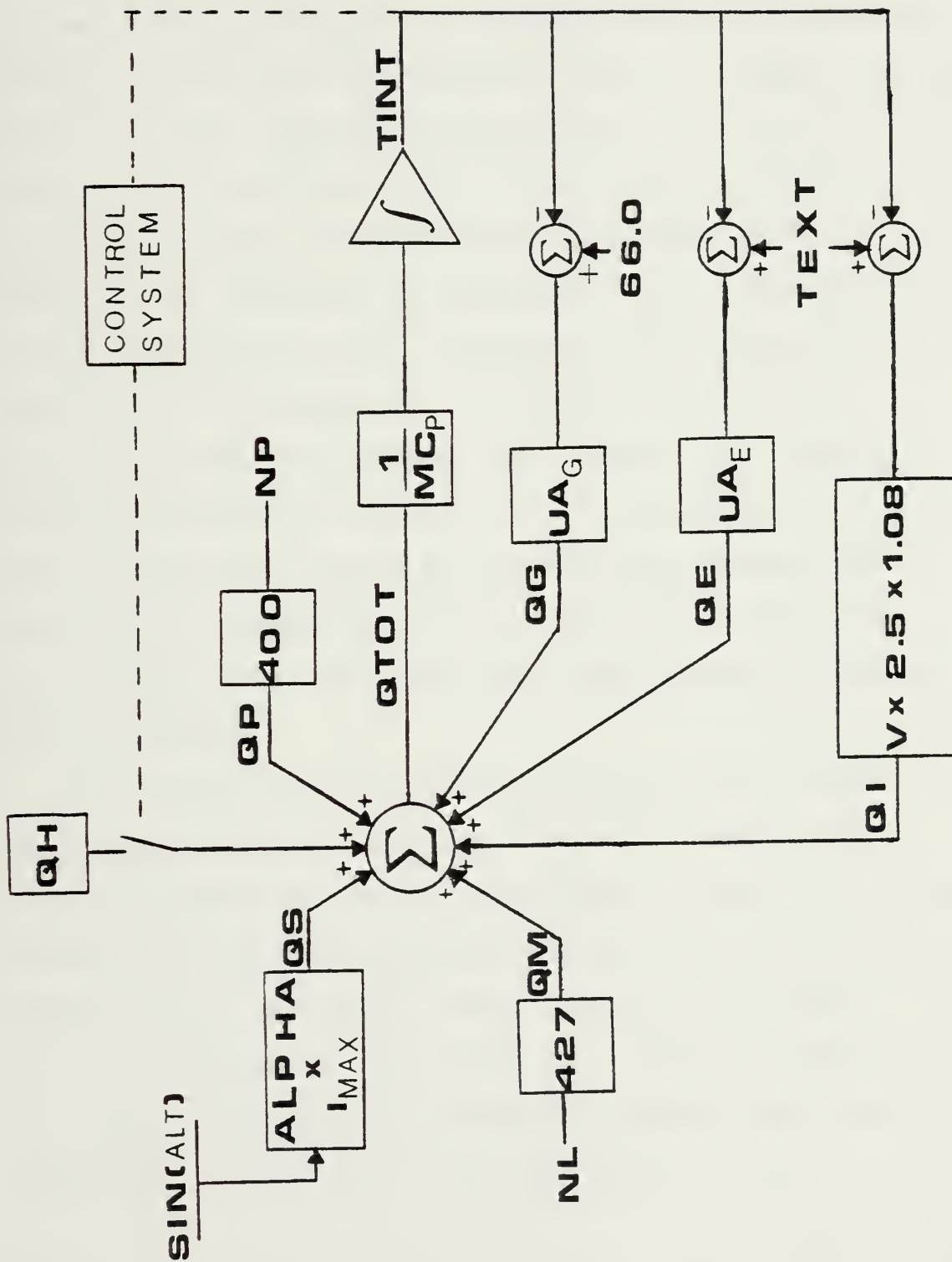
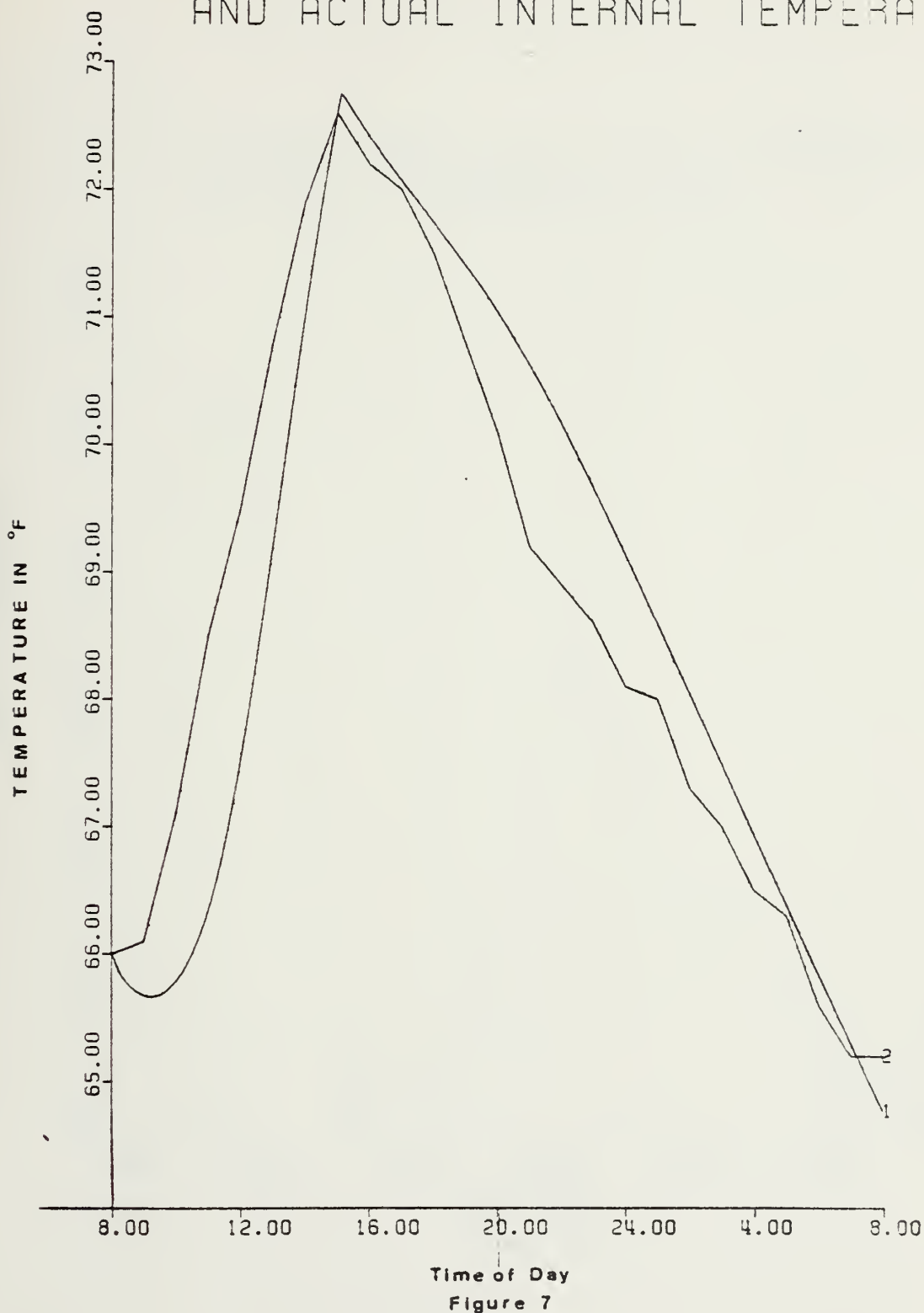


Figure 6
Signal Flow Graph

chapter. The driving force is divided by the mass and specific heat of the building material and then entered as the function to be integrated. The resulting output (TINT) is then used to recompute the temperature difference (DLT) between the internal and external (TEXT) air temperature and the ground loss temperature difference. An error calculation is then made between the actual internal temperature and the calculated value; then the important values are tabulated and displayed in graphical form. A complete copy of the program as run for 18 October 1980 is contained in Appendix C. The comparison of this model with other existing models, particularly the Building Load Analysis System Thermodynamics model, was not done because the BLAST model arrived too late to be installed and become operational at the computer facility. It is hoped that work might be done with the BLAST simulation program in future thesis studies.

The following set of figures represents the outcome of the modeling effort. Figure (7) shows the actual and calculated temperatures in the building. Figure (8) is the graph of the absolute error between the two temperatures. Figure (9) is a piecewise linear graph of the actual external temperature surrounding the building. Figure (10) is a representation of the difference between the internal temperature (measured) and the actual outside air

CALCULATED INTERNAL TEMPERATURE AND ACTUAL INTERNAL TEMPERATURE



ERROR BETWEEN CALCULATED AND ACTUAL TEMPERATURE

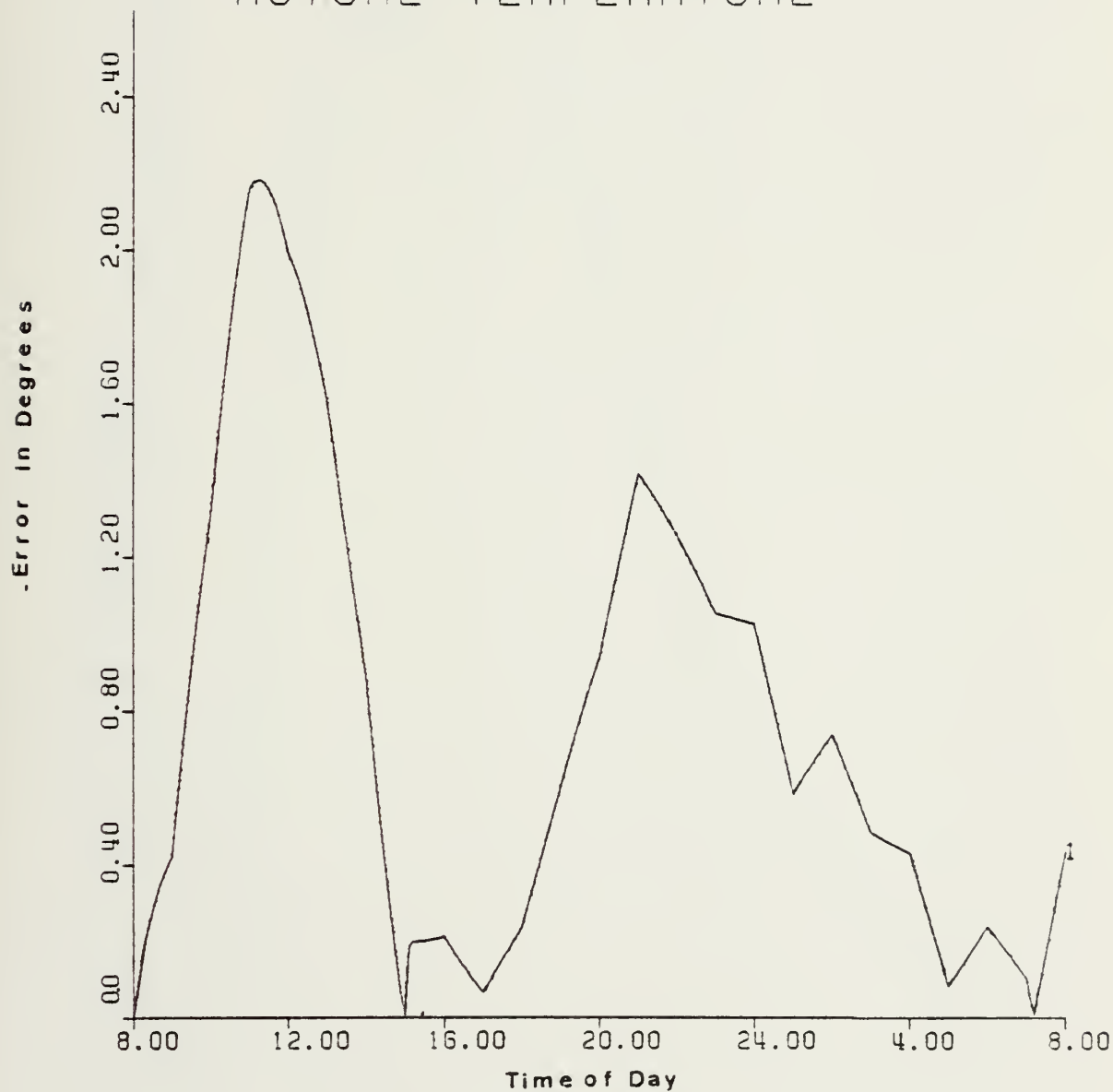


Figure 8

TEMPERATURE EXTERNAL

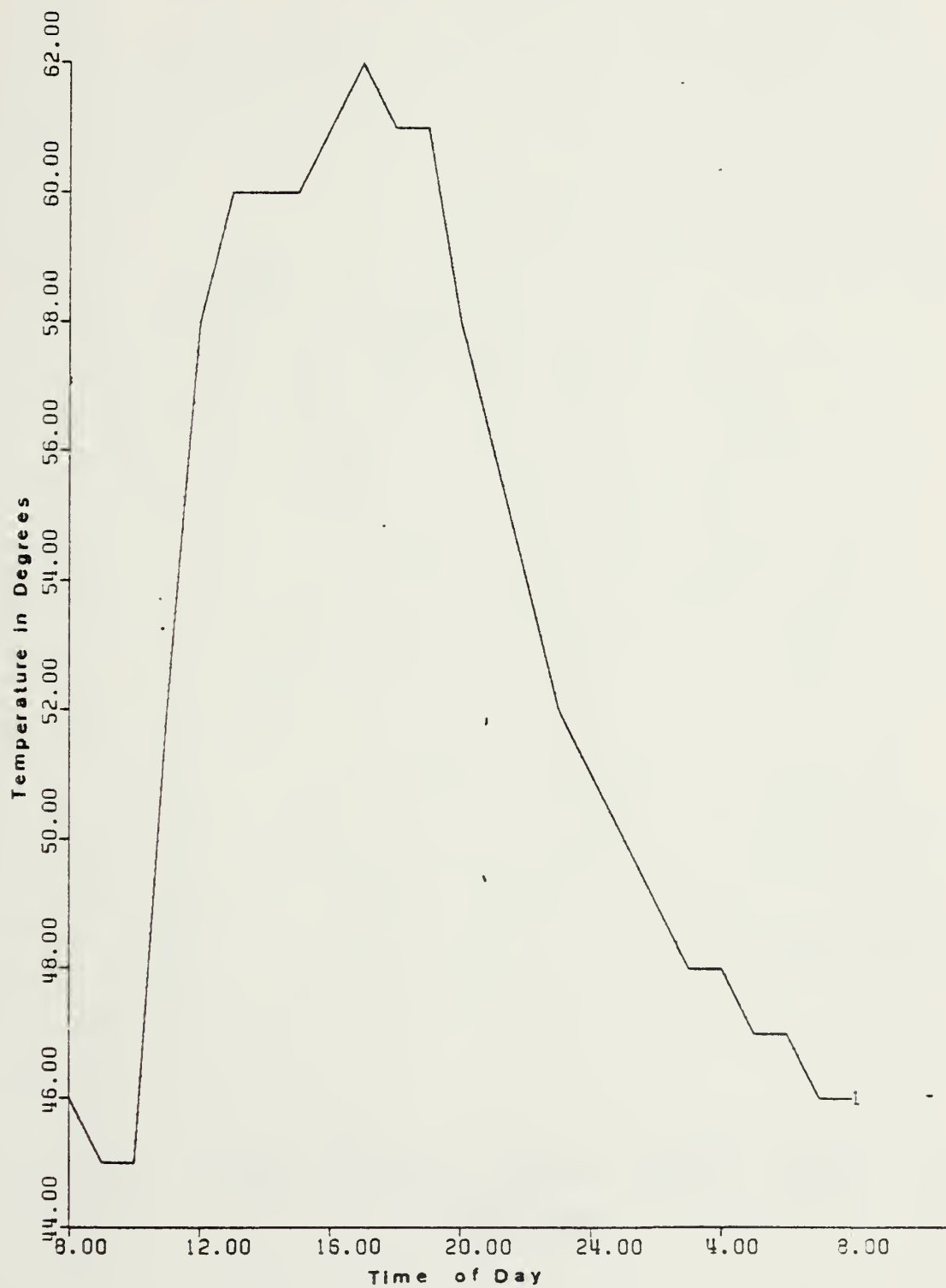


Figure 9

INTERNAL, EXTERNAL TEMPERATURE DIFFERENCE

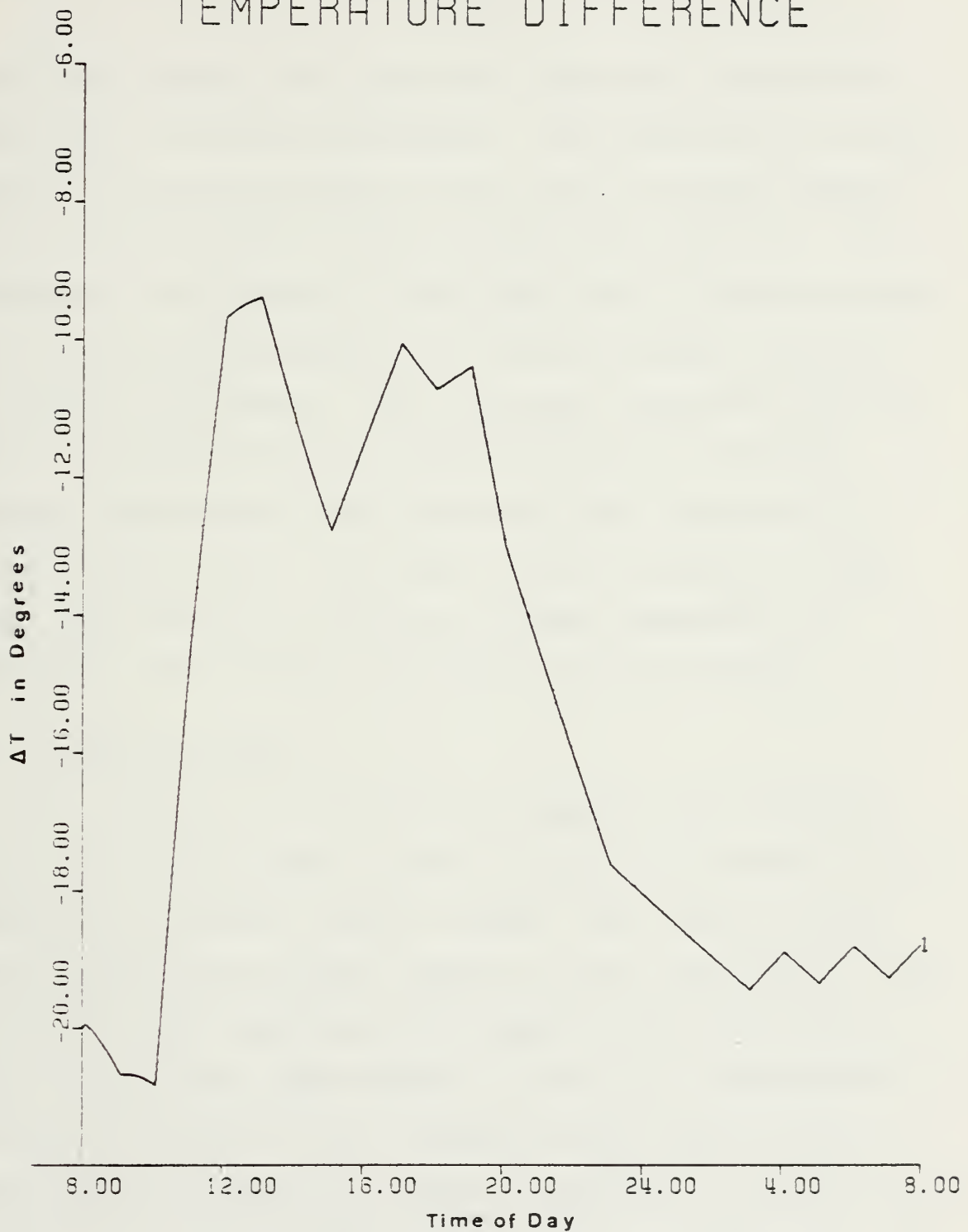


Figure 10

temperature. Finally, Figure (11) is the calculated total driving force (QTOT) on the building from all sources.

It can be noted that in Figure (8) that the maximum difference between the actual and calculated temperatures was about 2.5 degrees Fahrenheit. This difference is mostly due to the heating effects of the sun as indirect heating and not as sunlight actually striking the building. This effect was not included in the model and no reference could be found that even hinted as to how this effect could be included in the model. This particular simulation was the best of a series done for different days and different weather conditions. This particular model works best on clear or hazy days. The largest errors occurred on days when cloud cover or rain made it almost impossible to determine when the sun was actually on the building.

A. CONTROL AND COST

The object of the model was to emulate the characteristics of the building, so that it would be possible for the engineer to devise a control scheme. The control scheme would provide the maximum comfort for the individuals in the building, while minimizing the amount of fuel necessary to keep the building comfortable. In order for the engineer to devise the optimal control scheme he must place a price on each of the parameters he wishes to optimize. This price is referred to as the "cost" of that particular parameter, the

Q DOT TOTAL

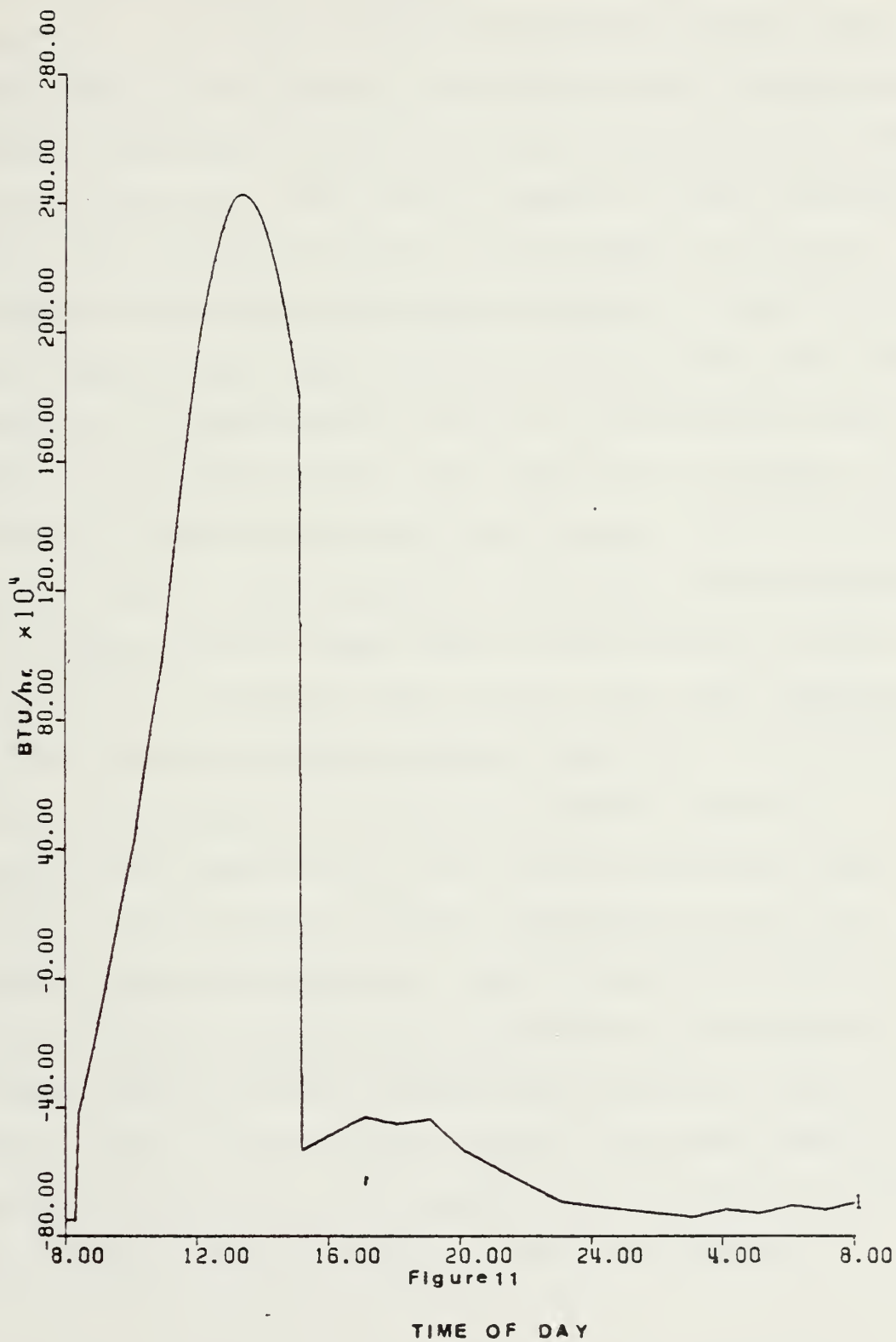


Figure 11

cost of fuel is easy to place a value on, but the "cost" of human comfort while occupying the building is hard to determine. In 1979, the Naval Postgraduate School spent over \$240,000 for natural gas, which is used as the primary fuel for heating. In 1980, the price has more than doubled. As for selecting a cost for the comfort of the individual, the health community has still been unable to place an estimate on how the performance of people is affected by the environment except under extreme working conditions. The engineer is faced with the problem of selecting a cost and then of selecting the best cost function to optimize. The ability to pick the correct costs is more of an art than a science, and is based mostly on intuition and experience. The present control theory used on the Honeywell system is one based on a minimum time response, when the temperature in the building reaches a preset temperature of 65 degrees the system immediately allows the maximum amount of steam/energy available to flow into the building, thus raising the building's internal temperature back to a desired level (67 degrees). The only modifications to that type of control system have been made by overriding the on/off function of the program during specific times of the day or night. This override reduces the energy used by the building while it is not occupied, but it may not be the most energy efficient method to heat the building.

Different "cost functions" will produce different types of control functions. The minimum time response cost function is but one of many cost functions which might be considered for the control of Bullard Hall's heating system. Another cost function to be considered could be the minimum fuel cost function. This cost function attempts to meet the system requirements (maintaining the temperature in the building) while expending the least amount of fuel. Again insufficient time was available to develop any new control scheme for the temperature control in the building using the cost functions previously mentioned. One other factor which previously had not been considered in the control scheme is the use of the ventilation fans as a control mechanism. If the fans on the roof were connected by an air-handling system and used to recirculate the air in the building as well as just exhaust the internal air, the building's internal environment would improve due to the cooling of hot spots (the south facing wall) and heating the colder areas in the building (Room 112). These ideas again are only suggestions in the hope that someone else may attempt to use the existing knowledge and computer models (particularly the BLAST model) and pursue a more energy efficient control program.

IV. DATA COLLECTION AND INSTRUMENTATION

The main objective here was to develop a working thermodynamic model of a building and verify that the model did indeed simulate the building. The problems of developing the model were far outweighed by the problems encountered in the collection and verification of data. The main parameter of interest, the internal building temperature was measured hourly for as many as three days at a time. Since remote temperature sensing and storage devices were not available, the data was collected by hand and recorded. This process alone was very time consuming. If further investigation into the thermodynamic effects of the environment are to be conducted, it is recommended that the first order of business be to build a set of remote sensing devices and tie them together to a microprocessor so that the data can be collected continuously.

The second biggest problem in the modeling process was to determine the amount of solar energy that was incident on the structure. A pyrlieliograph located at the Hopkins Marine Station in Pacific Grove was used to estimate the amount of solar energy that was available at the building under study. The instrument was approximately four miles from the site and could only really be used as a measuring

device when there were no clouds in the sky or when the total area was covered with fog. At one time the Naval Postgraduate School had an operational pyr heliometer but because of age and lack of funds the instrument has been allowed to become non-operational. This particular instrument would be advantageous to the Navy and the civilian community to have functional, since so little information is available about the amount of solar energy actually available on the peninsula. Recently the U.S. Army contracted to build over 300 homes at Fort Ord that will use solar panels as a booster for the hot water systems in the houses. The Army engineers who are responsible for the evaluation admit that the outlay of funds to install the solar systems may never be recovered by using the solar panels, but the information that they hope to gain concerning the area and the availability of solar energy in the area is considered to be worth the expense. Presently the Meteorology Department at the school provides the local news agencies with most of the temperature and meteorological data on the area. The Fleet Numerical Weather Center, which is not part of the school command, contains the facilities to evaluate almost any set of atmospheric conditions for the area with their facilities, yet they remain untapped.

The instrumentation availability and the collection of data are the most difficult tasks in developing the

simulation. Because of the upcoming computer replacement and the large volume of computer programs that were run at the school during the last three months, little time could be spent in trying to develop a more complete or reliable model. The BLAST model is considered by many in the engineering field to be the most accurate and complete system to study the effects of different control schemes on a structure. Since BLAST is incompatible with the present computer system and required the use of the computer facilities at the Weather Center, little testing or comparison of the two models was done.

V. CONCLUSION

The actual model developed is extremely simple and works very well under ideal conditions, even though the model fails to take into account the indirect solar gain caused by reflections from other buildings and diffused light. The model, though incapable of handling partially cloudy or rainy days, is an aid for those people who have no conception of how the temperature inside a building will react to the outside environment. The model, though simple, contains all of the major forces acting on the building and can be used in developing a better control scheme for the temperature control in Bullard Hall.

The major reason for using the model was to gain knowledge concerning conservation and more effective use of solar energy. Presently, the U.S. Navy and the Naval Research Laboratory have more facilities and programs aimed at conserving petroleum products and using renewable energy than any other branch of government except the Department of Energy, yet the officers at this institution must look elsewhere for information on energy programs and conservation measures. A large portion of this school's graduates go on to jobs where it would be possible to implement energy conservation measures and save the Navy large sums of money,

but few have ever been exposed to the information they need. Information on conservation and alternative energy sources is not readily available and few students have pursued any courses of study dealing with energy conservation.

Most of the structures at the Naval Postgraduate School are not designed to be energy efficient, but with research efforts by students and faculty many of the buildings could be modified and used to demonstrate energy saving ideas and methods. Bullard Hall, as can be ascertained, is a structure that wastes energy. The building has too many doors, some of them never used. The thermal circulation in the building is inefficient, yet no one has suggested a modification to the present ventilation system which now exhausts the warmest air, even when shut off. Room 112 is a proverbial ice box; the sun never shines into the space and the temperature is consistently five to ten degrees colder than the rest of the building. The room is glass on two sides and the blinds are almost always closed. This prevents little reflected light from entering the back of the room, but allows energy to escape. The room also contains a set of doors that are never used. These doors do not seal tightly and the room is perpetually drafty.

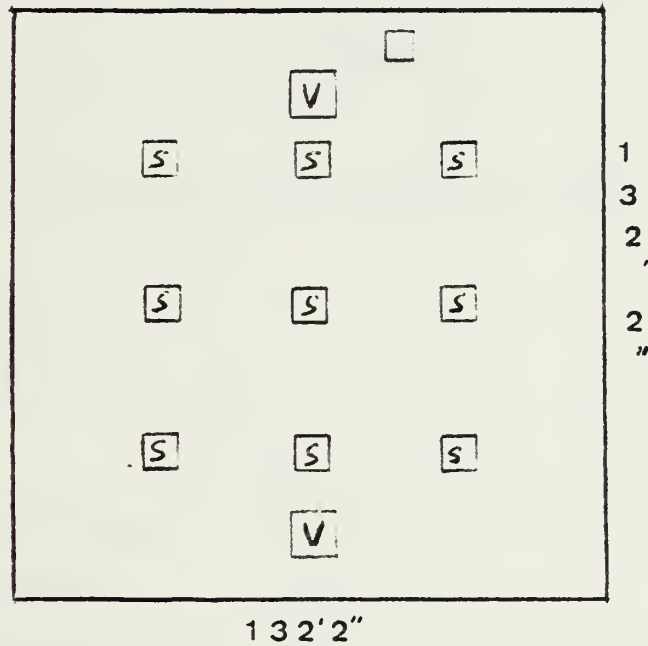
One issue this work did uncover was the question of whether sufficient instrumentation existed at the boiler

plant to actually measure the energy being converted in the boilers and where this energy goes. Few of the readings taken by the boiler plant operator have any meaning and much of the instrumentation is either out of calibration or inoperative. An example of this is the house steam differential pressure detector. In May of 1979 something either broke in the instrumentation circuits or the differential pressure cell became inoperative due to an obstruction or a part failure in the cell. Either way, the recorded steam demand immediately dropped to one half of what it had been, without any change in any of the other measurable parameters. To the author's knowledge the instrument is still out of service and no attempt has been made to check the problem.

Suggestions for future study and investigation include:

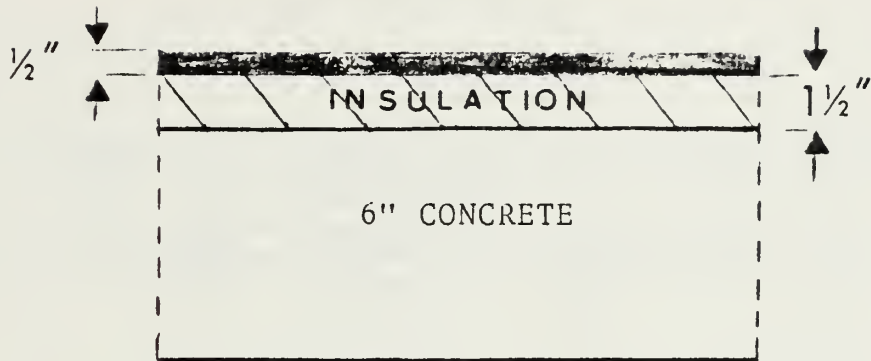
- 1) A joint Mechanical and Electrical Engineering Department group designing and constructing a microprocessor based remote temperature monitoring and data collection system.
- 2) A Mechanical Engineering Department study and cost analysis of installing insulation in isolated rooms and energizing air-handling equipment in Bullard Hall.
- 3) A repair of the steam plant instrumentation and other energy monitoring equipment at the Naval Postgraduate School.

APPENDIX A
THERMAL CONDUCTANCE DETERMINATION
Roof



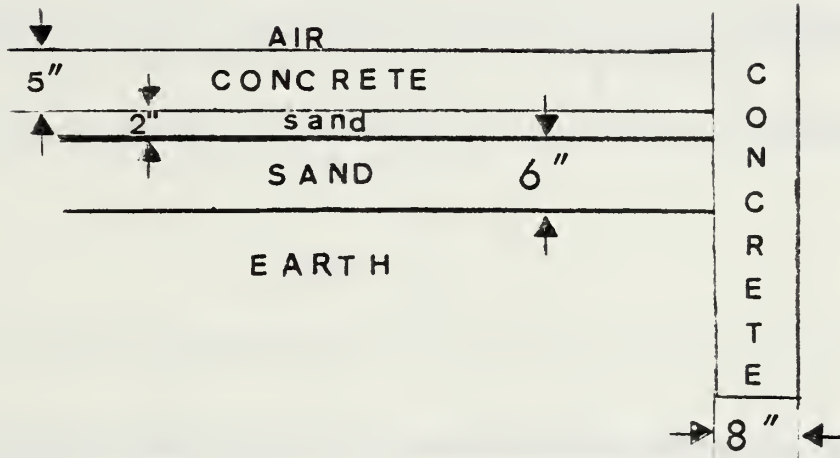
9 SKYLIGHTS (S)	U = 1.15
2 VENT DUCTS (V)	U = 1.63
1 SCUTTLE	U = 1.63

Roof Section



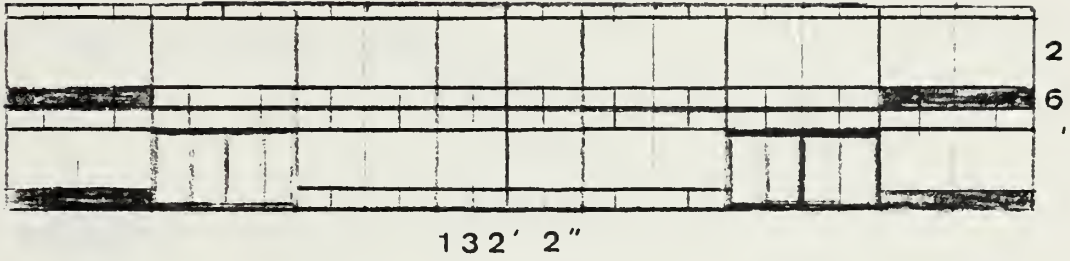
	R
AIR 15 Kts.	0.17
$\frac{1}{2}$ " ROOFING	0.15
$1\frac{1}{2}$ " INSULATION	4.17
6" CONCRETE	0.48
INSIDE AIR	<u>0.64</u>
R_t	5.61
$U = 1/R_t = 0.17$	

Floor Section



	R
FLOOR AIR	1.70
5" CONCRETE	0.40
2" SAND	0.0
WATER PROOF PAPER	0.0
6" SAND	<u>0.0</u>
R_t	2.10
$U = 1/R_t = 0.48$	

Wall Sections
North and South Faces



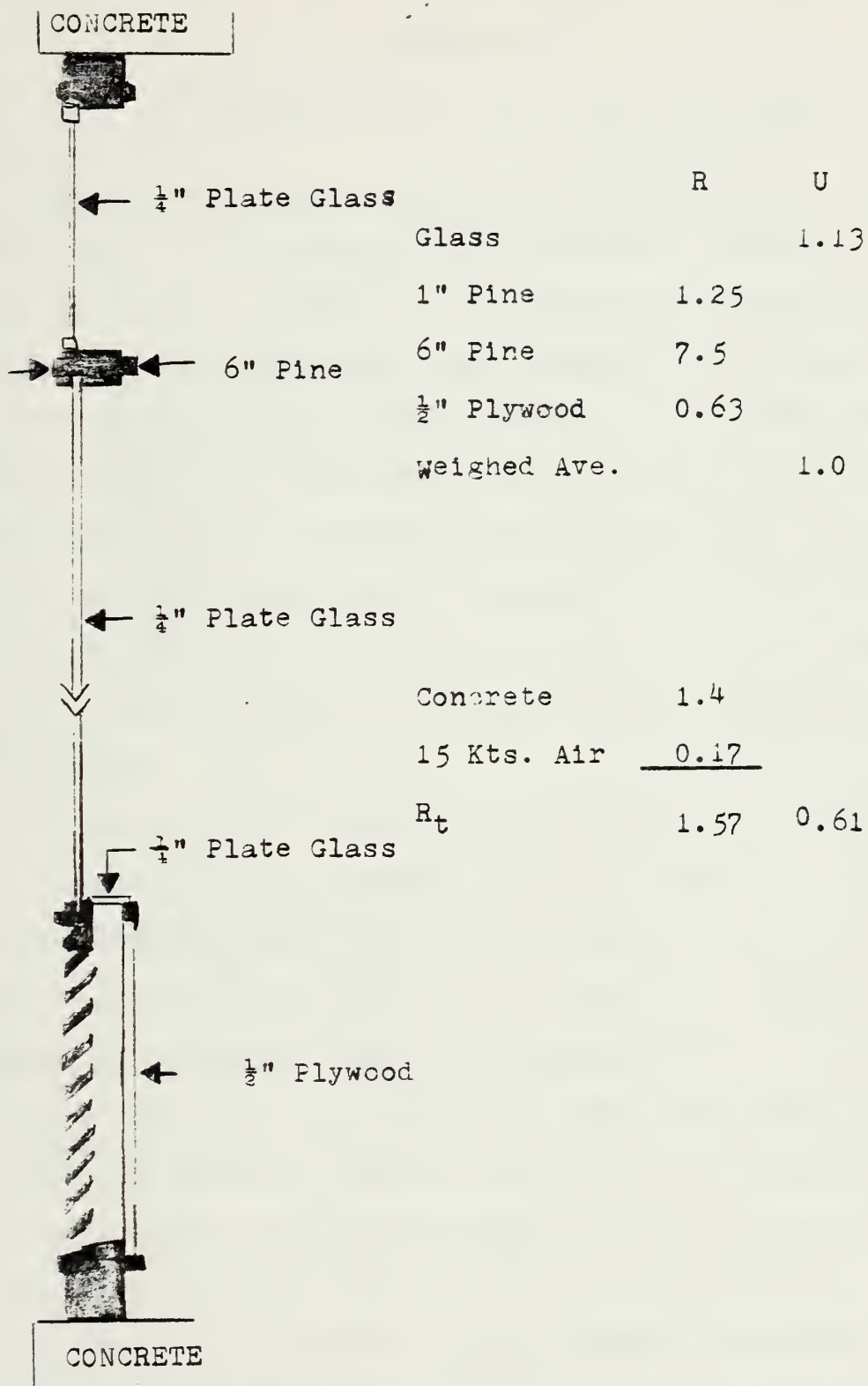
East Face



West Face



Wall Section

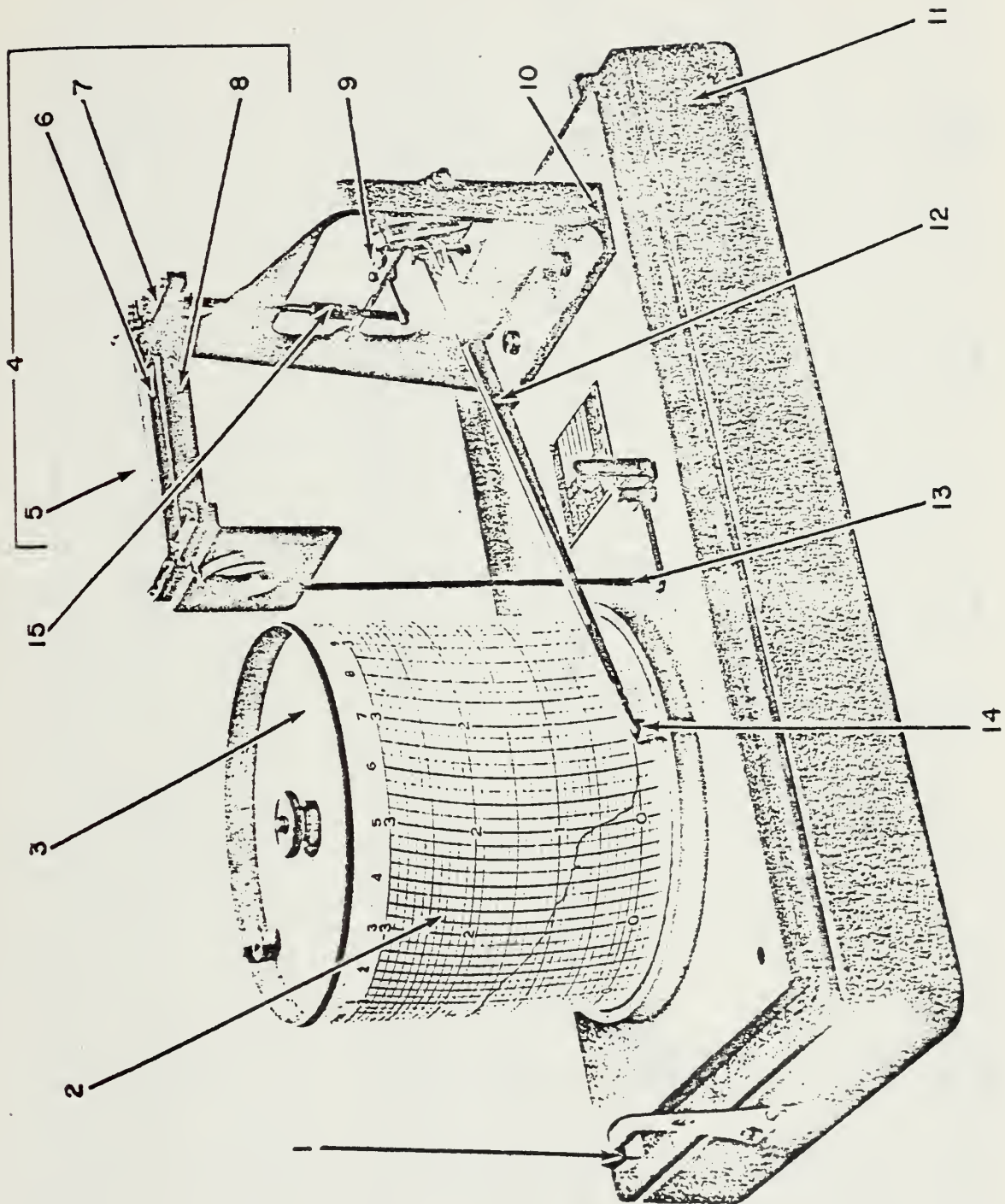


APPENDIX B

PRYHELIOGRAPH DATA AND IMAX ASSUMPTIONS

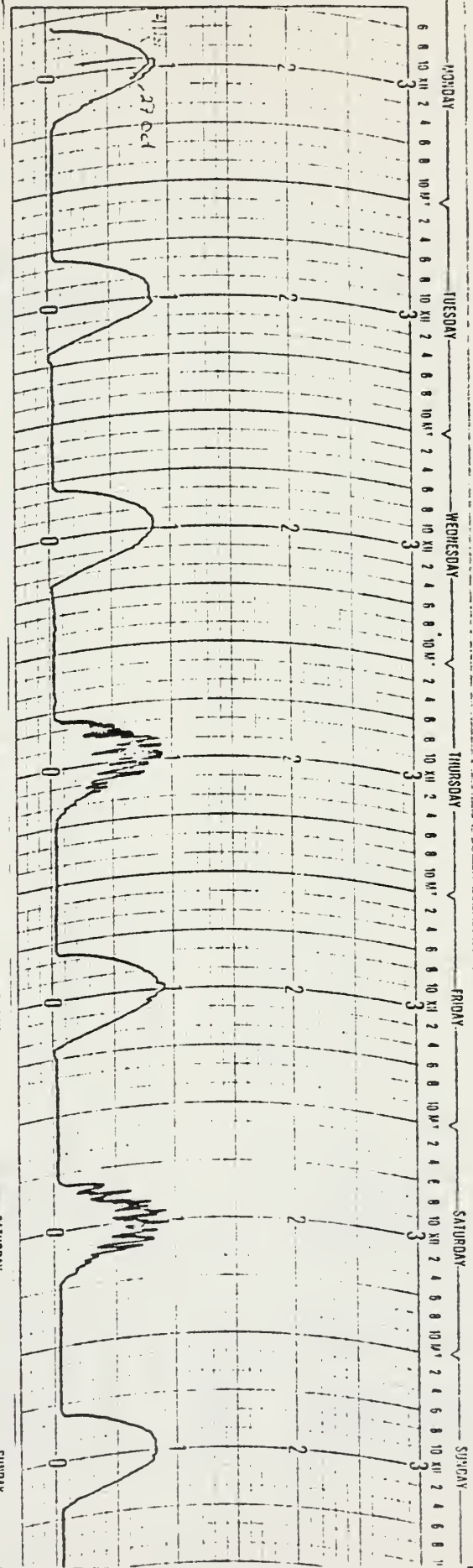
The following chart represents a complete data week from the Hopkins Marine Stations pyrheliograph installed in Pacific Grove. By using the calibration procedures in the Belfort Instrument Manual which accompanied the instrument a base line measurement of 430 BTU/ft. hr was established at approximately 12.5 mm. above the zero input line. Using this base line as a reference the maximum solar intensity for a particular day can be computed by forming a ratio of the maximum height as compared to the 12.5 mm. reference line. A picture of the instrument is also included for information.

Using the data collected for September and October 1980 was compared to the expected values for the area as recorded in the ASHRAE Guide and Data Book, results were within 8% of the expected value quoted for the area. In the model the parameter Alpha represents the maximum incident solar energy recorded for that day times 0.85. The 0.85 correction figure was chosen to indicate the amount of energy incident on the building which is absorbed. This approximation is based on data taken from the Reference 11 "Thermal Properties of Buildings" on the estimated absorption coefficient for concrete.



PYRHELIOGRAPH-OPEN

13'



APPENDIX C COMPUTER PROGRAM

```

//IBERT000 JOB (1422,0206,EA91),'THESIS',TIME=2
// EXEC DSL
//DSL.INPUT DD *
//TITLE BULLARD HALL SIMULATION 18 OCTOBER 1980
//INTEGER NPLOT
//CONST NPLOT= 1
**
** EXTERNAL TEMPERATURE
**
AFGEN TEMP = 0,46.0, 1,45.0, 2,45.0, 3,52.0, 4,58.0,....
          5,60.0, 6,60.0, 7,60.0,8,61.0, 9,62.0, 10,61.0,....
          11,61.0,12,58.0,13,56.0,14,54.0,15,52.0,16,51.0,....
          17,50.0,18,49.0,19,48.0,20,48.0,21,47.0,22,47.0,....
          23,46.0,24,46.0
**
** ACTUAL INTERNAL TEMPERATURE
**
AFGEN ATEM = 0,66.1,66.1,2,67.1,3,68.5,4,69.5,5,70.8,6,71.9,....
          7,72.6,8,72.2,9,72.1,10,71.5,11,70.8,12,70.1,13,69.2,....
          14,68.9,15,68.6,16,68.1,17,68.1,18,67.3,19,67.2,20,66.5,....
          21,66.3,22,65.6,23,65.2,24,65.2
**
** LATITUDE AND LONGITUDE
**
PARAM LAT = 36.595
PARAM LON = 121.875
**
** ANGLE OF EAST WALL TO NORTH(IN DECIMAL)
**
PARAM DE = 37.75
**
** JULIAN DATE AND LOCAL TIME (DST)
**
PARAM JD = 292.0
PARAM LT = 8.0
PARAM DST = -1.0
**
** BUILDING ENVELOPE PARAMETERS
**
PARAM UAE =17149.91
PARAM UAG = 8384.65
PARAM MT = 8479189.5
PARAM CPT = 0.156
PARAM AE = 3436.33
PARAM AN = 3436.33
PARAM AR = 17468.0278
PARAM NP =0.0
PARAM NL =0.0

```



```

* * * * * NAUTICAL ALMANAC DATA
* * * * * GHA OF SUN
PARAM AA = 16.0
PARAM W = 275.0
PARAM AOG = 5943.6412
PARAM AIG = 5760.8174
PARAM A2G = -0.3052
PARAM A3G = -0.0558
PARAM A4G = -0.0039
PARAM A5G = 0.0059
* * * * * DECLINATION OF SUN
PARAM AOD = -9.2273
PARAM A1D = -5.8549
PARAM A2D = 0.2816
PARAM A3D = 0.0649
PARAM A4D = 0.0025
PARAM A5D = 0.0067
* * * * * ATMOSPHERIC TRANSMITTANCE
PARAM ALPHA = 0.62
*
CONTRL FINIM = 24.0, DELT=0.1, DELS=0.1
INITIAL
TINTO = 66.0
TINT = 66.0
ON = 0.0
PI = 2.0 * ARSIN(1.0)
DRAD = PI/180.0
DYNAMIC
TEXT = AFGEN(TEMP, TIME)
* * * * * CALCULATION OF ALTITUDE AND AZIMUTH
GMT = LT + TIME + 8.0 + DST
XT = ((JD + (GMT/24.0) - W)/AA) - 1
GHA = AOG + (((A5G*XT + A4G)*XT + A3G)*XT + A2G)*XT + A1G)*XT
DEC = AOD + (((A5D*XT + A4D)*XT + A3D)*XT + A2D)*XT + A1D)*XT
LH = GHA - LON + 360.0
LHA = AMOD(LH, 360.0)
RLHA = LHA * DRAD
RDEC = DEC * DRAD
RLAT = LAT * DRAD
Z = SIN(RLAT)* SIN(RDEC) + COS(RLAT)* COS(RDEC) * COS(RLHA)

```



```

RALT = ARSIN(Z)
ALT = RALT/DRAD
Y = SIN(RLHA)/(COS(RLHA)*SIN(RLAT))- TAN(RDEC)* COS(RLAT))
RAZ = ATAN(Y)
IF (Y.LT.0.0)GO TO 2
IF (LHA.LT.180.0)GO TO 1
AZM = RAZ/DRAD
GO TO 10
1  AZM = RAZ/DRAD +180.0
GO TO 10
2  IF (LHA.LT.180.0)GO TO 3
AZM = RAZ/DRAD +180.0
GO TO 10
3  AZM = RAZ/DRAD + 360.0
10 CONTINUE
RAZM = AZM *DRAD
RDE = DE * DRAD
SRDE = SIN(RDE)
SPRDE = SIN(PI - RDE)
CRDE = COS(RDE)
CPRDE = COS(PI - RDE)
CC = COS(RALT) * COS(RAZM)
CS = COS(RALT) * SIN(RAZM)

SOLAR HEAT GAIN

NSE = AE * (SRDE * CC + CRDE * CS)
NSN = AN * (SPRDE * CC -CPRDE * CS)
NSW = AE * (-SRDE * CC -CRDE * CS)
NSS = AN * (-SPRDE * CC + CPRDE * CS)
NSR = AR * SIN (RALT)

SUN'S ANGULAR CUTOUTS

IF (TIME.LT.5.0)GO TO 11
IF (ALT.GT.34.0)GO TO 12
ANDR = 0.0
GO TO 13
11 IF(ALT.GT.10.0) GO TO 12
ANOR = 0.0
GO TO 13
12 AANOR = ABS (NSE)+ABS (NSN)+ABS (NSW)+ABS(NSS)
ANOR = (NSE +NSN+NSW+NSS+AANOR)/2.0 +NSR
13 CONTINUE
QS = ANOR * ALPHA * Z * 429.2

***
***
***
***

```



```

** STEAM HEAT GAIN
IF (TINT.LE.65.0)GO TO 20
IF (TINT.GE.67.0)GO TO 19
IF (ON.GE.1.0)GO TO 20
19 QH = 0.0
   QN = 0.0
   GO TO 21
20 QH = 1937600.0
   QN = 1.0
21 CONTINUE
**
** DERIVATIVE
**
** ENVELOPE HEAT GAIN
QE = UAE * DLT
QG = UAG * (66.0 -TINT)
DLT = TEXT - TINT
**
** INFILTRATION LOSS
QI = 0.018 * 454168.722 * 2.5 * DLT
**
** BODY HEAT GAIN
QP = NP * 400.0
**
** MACHINERY HEAT GAIN
QM = NL * 742.54
**
** PLANT
QTOT= QE+QG+QI+QS+QH+QM+QP
TDOT= QTOT/(MT*CPT)
TINT= INTGRL(TINTO,TDOT)
**
** PRINT 0.2,TINT,ACT,ADT,TEXT,DLT,QTOT
**
** SAMPLE
**
** ERROR CALCULATION
ACT = AFGEN(ATEM,TIME)
DT = TINT - ACT
ADT = ABS(DT)

```



```

*
CALL DRWG(1,1,TIME,TINT)
CALL DRWG(1,2,TIME,ACT)
CALL DRWG(2,1,TIME,ADT)
CALL DRWG(3,1,TIME,TEXT)
CALL DRWG(4,1,TIME,QTOT)
CALL DRWG(5,1,TIME,DLT)
TERMINAL
CALL ENDRW(NPLOT)
END
STOP
//PLOT.SYSIN DD *
      CALCULATED INTERNAL TEMPERATURE
      AND ACTUAL INTERNAL TEMPERATURE
      ERROR BETWEEN CALCULATED AND
      ACTUAL TEMPERATURE
      TEMPERATURE EXTERNAL
      Q DOT TOTAL
      INTERNAL, EXTERNAL
      TEMPERATURE DIFFERENCE

```


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